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ASSESSMENT OF GROUNDWATER RESPONSE AND SOIL MOISTURE FLUCTUATIONS IN THE MUGELLO BASIN (CENTRAL ITALY)

ABSTRACT. Extreme meteorological events such as heavy rainstorms are considered to increase due to global warming. The consequences of such events can be manifold, and might cause massive interferences of the hydrological system of a landscape. Particularly the intramontane basins of the Apennine in Italy are frequently threatened by extreme rainfall events that cause severe damage on buildings and infrastructure. Moreover, the lithological and geomorphological settings of these basins, which depict the products of a complex landscape history, amplify these threats. In order to develop possible mitigation strategies, it is crucial to assess landscape functioning by analysing hydrological processes of the landscape system. In this study, we conducted spatially distributed and dynamic hydrological modelling on a catchment in the intramontane basin of the Mugello valley in Tuscany, Italy. Foremost, measurements of saturated hydraulic conductivity and texture analyses were performed to estimate both infiltration and hydraulic conductivity of the surface and topsoil, respectively. We regionalised the collected data with a stochastic gradient treeboost method for the whole catchment. Soil depth was estimated with a simple sine-cosine-slope relation, whereas, hydropedologic parameters for the hydrological model were estimated with pedotransfer-functions applied on the collected infiltration data. We modelled a period of 100 days, representing each day per time step. A synthetic rainfall period was compiled based on measured data from meteorological stations within the Mugello basin. To produce a reliable synthetic rainfall data set, the estimated precipitation values were set in comparison to calculated return periods for extreme events of all available meteorological station. To assess the diversity of the hydrological response of several locations in the catchment, six semi-random test locations were located on hillslopes and spots were sedimentation is apparent. The results show that groundwater and soil moisture fluctuations appear to be significantly different for both hillslopes and areas were sediments are deposited. The differences cannot be explained by the topographical settings but rather by the approximated thickness of the weathered zone and the spatial diversity of the hydropedological properties of the soil.

KEYWORDS: geographical hydrology; STARWARS/Probstab; groundwater; soil moisture; lacustrine sediments; Mugello;

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INTRODUCTION

Global warming has severe effects of changes in annual precipitation values and the frequency and intensity of extreme events [Crisci et al. 2002]. Italy, and in particular the Apennine, is threatened by extreme rainstorms and their diverse impacts on the landscape. The hydrological processes and imbalances that can be triggered by extreme rainfall events appear to be very complex. Several studies have been conducted to analyse the hydrological effects of certain rainfall events on Mediterranean landscapes [Brath et al., 2006; Brath et al., 2004; Montanari & Toth, 2007]. Spatially-distributed hydrological models such as TOPMODEL [Beven & Kirkby, 1979] or WEPP [Nearing et al., 1989] are able to assess and predict hydrological responses of landscapes to rainstorms. Several studies successfully applied similar hydrological models for study sites in the Mediterranean to show the hydrological impact of rainstorms and the triggered sediment dynamics [Crisci et al., 2002; Brath et al., 2006; Brath et al., 2004; Montanari & Koutsoyiannis, 2012]. The Mugello basin in Tuscany is of highly interest considering its landscape evolution and the geomorphological processes. The diverse lithological and geomorphological setting as well as land cover changes and anthropogenic impacts combined with frequent extreme rainstorms or long precipitation periods let the Mugello being an example for the major geomorphological challenges man has to face in times of global warming.

In this study, we assess the hydrological response of some small Torrents, tributaries of the Sieve River draining the Mugello basin. Hereto, data on saturated hydraulic conductivity, pedologic and climatic conditions were collected to conduct basic hydrological modelling. A particular focus was set on the hydrological response of the catchment after a heavy rainfall period that typically can occur in spring and autumn. Therefore, we produced synthetic rainfall data of a representative rainstorm event that are based on rainfall data from meteorological stations within the Mugello basin. Saturated hydraulic conductivity and infiltration were measured to estimate the infiltration capacity of the topsoil and thus to predict when the soil column becomes saturated and runoff or subsurface flow along a lithic boundary can occur. Rainfall and hydraulic conductivity data were used as input information for a physically based water response model. The results reveal insights in the dynamics of the hydrological regime and the potentials of the related sediment fluxes. This information is expected to provide better knowledge about groundwater fluctuations and surface runoff during rainstorms that are typical for the region.

STUDY AREA

The Mugello, a typical Intra-Apennine basin with an area of about 20 km^2, is located approximately 30 km north of Florence, Tuscany, Italy (Fig. 1). The intermontane basin is drained by the river Sieve, a left tributary of the Arno river [Garfagnoli et al., 2013]. Our study area is a small hydrological catchment in the northwestern part of the Mugello within the administrative borders of Barberino di Mugello and Scarperia as well as San Piero. The most prominent town within the site is Barberino di Mugello close to the autostrada A1 that passes through the western part of the basin. The studied catchment has a size of ~ 6.7 km^2 and is drained by several torrents to the South into the Lago di Bilancino or directly into the Sieve river, respectively. These are from West to East: Torrente Calecchia, Torrente Sorcella, Torrente Travaiano, and Torrente Anguidola. Since the town of Galliano is located in the centre of our study area, the investigated catchment that contains all the torrents mentioned is named 'Galliano catchment' throughout the whole paper.

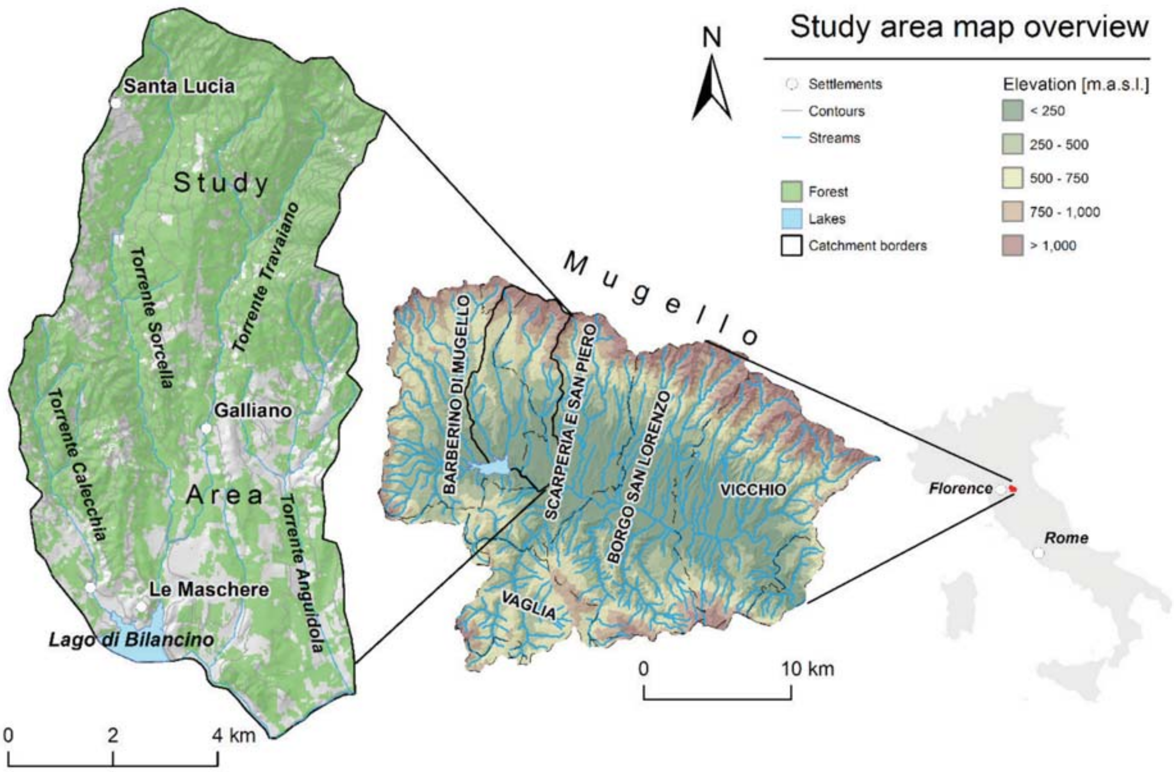

Fig. 1. Study area within the Mugello basin.

The lithological setting was described by former studies that were based on extensive field mapping and sedimentological analyses [Benvenuti 1994, 1997; Benvenuti & Papini, 1997; Sanesi, 1965]. The geology of the area contains mainly alluvial-lacustrine deposits of the Pliocene and Upper Pleistocene which is typical for comparable intramontane (or periphel, after Martini& Sagri, 1993] basins of the Northern Apennine. Studies that provided structural and stratigraphic data in the 1990s suggest that the Mugello basin formed by alternating tectonic compression and crustal extension [Benvenuti, 2003; Boccaletti et al., 1997]. According to Vai [2001] the Mugello developed throughout the Tertiary in a continental collisional setting. The Galliano catchment consists of calcareous claystones partly interrupted by Ligurid limestones and serpentinites that tectonically overly early-middle Miocene sandstones and siltstones [Benvenuti & Martini, 2002]. Benvenuti & Papini [1997] distinguished two phases of infilling: a fluvio-lacustrine phase (approx. late Pliocene to early Pleistocene) and an alluvial phase (approx. early Pleistocene to Holocene). During the fluvio-lacustrine phase, the basin was filled up to 100 m with peat and silty clay indicating a palustrine environment, particularly in the western part of the basin. The alluvial phase, however, can be subdivided in three major periods of base-level fall, leading distinctively to terracing of the fluvio-lacustrine and alluvial sediments [Sanesi, 1965].

Most of the soils in the Scarperia area and surroundings originate from silty-clayey sediments [Zanchi, 1988] and thus contain high amounts of clay minerals. However, the fluvio-lacustrine bed-material mostly consists of layers of packed and loose gravels as well as silty-sand layers with respectively low amount of clay. These sediments are prevalent in streambanks that are particularly affected by undercutting of the Sieve River [Rinaldi & Casagli, 1999]. Intense erosional and mass wasting processes such as sheet erosion and landslides threaten the slopes at the margins of the Mugello basin.

The study area is agriculturally used, particularly the valley bottoms. Mainly annual crops such as grain maize, barley and durum wheat are cultivated. On the sloping areas above the lacustrine sediments also olive groves, orchards and vineyards occur [Benvenuti, 2003; Piorr et al., 2009]. Forests are primarily located on higher altitude at the ridges of the basins margins. The valley itself was highly affected by anthropogenic induced land use changes. Valuable contributions on human-landscape relations and anthropogenic impacts on the land cover were conducted by [Rinaldi & Rodolfi, 1995]. Agricultural activity of man can be dated back before 1600 A.D. with starting bank adjustments of the channel. From 1600 to 1900 A.D. a progressive uncontrolled deforestation started combined with intense aggradation in the inter-embankment zones of the Sieve River [Rinaldi & Casagli, 1999]. Reforestation and upland sediment retention started after 1900 A.D. [Rinaldi& Casagli, 1999; Rinaldi & Rodolfi, 1995].

Climate is Mediterranean with an annual precipitation reaching from 890 mm near San Piero a Sieve (211 m. a. s. l.) and 1300 mm at Monte di Fo' (820 m a. s. l.), due to orography. The monthly maximum in Borgo San Lorenzo is about 120 mm in November, while the minimum is about 20 mm in July. Annual mean temperature is about 14 °C. The monthly maximum in July and August reaches 23.5 °C and the minimum is about 5 °C in January. The mean annual temperature at Monte di Fo' is about 11 °C.Daily precipitation amounts with a return period of 1 year reach from 35 mm at S. Piero a Sieve to 50 mm at Monte di Fo'. 5 year events range from 60 mm to 90 mm and 50 year events from 90 mm to 150 mm (Fig. 2). Values of the other meteorological stations close to the study area are show the same range. The upper parts of the catchments are affected by stronger events than the lower

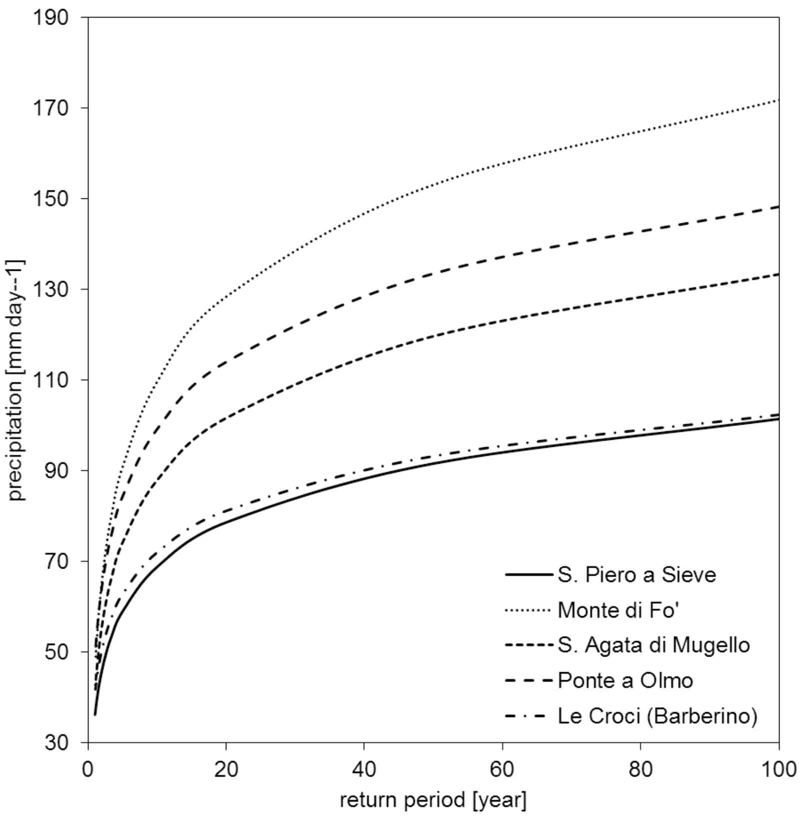

Fig. 2. Interpolated (1-10 year) and extrapolated (11-100 year) extreme precipitation events, based on data by SIR (2014).

areas. The highest amount between 1992 and 2013 with 121.5 mm was reported on 8th of August 1997 at S. Piero a Sieve (five centennial event; SIR 2014).

MATERIAL AND METHODS

Hydropedologic measurements and soil identification

Saturated hydraulic conductivity was measured at 70 locations in the lower part of the Galliano catchment. We used both IL-2700 Hood-Infiltrometer [Umwelt Gerätetechnik GmbH] and a constant head permeameter [Amoozemeter, Ksat Ltd, Amoozegar, 1989]. Infiltration rate was measured with the IL-2700 under saturated conditions or 0-tension respectively, to provide a better comparability with the Ksat values of the Amoozemeter. Ksat was measured in the topsoil (< 25 cm) (Fig. 3).

We applied a stochastic approach based on logistic regression technique [Atkinson et al. 1998] using the measured Ksat values and as dependent variable and environmental predictor variables delineated from the DEM such as slope and elevation following [Reuter et al. 2009]as independent variable. The dataset was split in train (80% of Ntot) and test data (20% of Ntot). Hence, the model was calibrated with the train data and validated with the test data. We evaluated the performance of the model using the receiver operator characteristic (ROC) curve for training and test data. According to(Lemeshow & Hosmer, 1982], AUC values exceeding 0.62 indicate acceptable predictions.

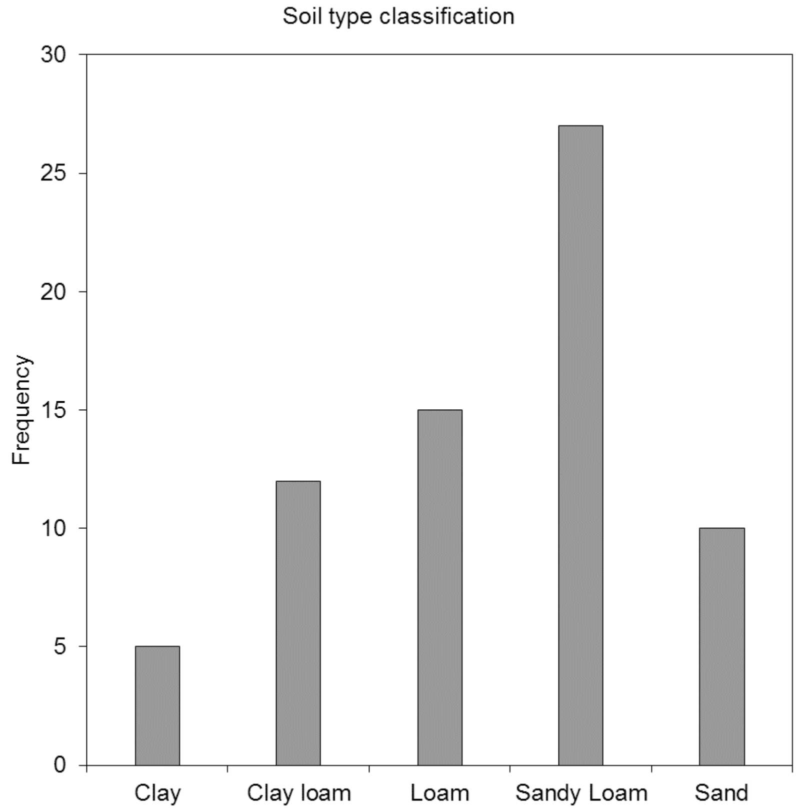

Fig. 3. Soil texture classification obtained from soil profiles and Ksat values of the sampled locations.

For the preparation of the hydrological input parameter (cf. chapter 3.3) pedotransfer functions were used to gather information about the soil layers > 25 cm. Therefore, we conducted soil type classifications with finger test for texture approximation on six soil profiles. The soil texture information were then implemented in pedotransfer relations according to Saxton et al. [1986] and Saxton & Rawls [2006]. The application of these relations yield information about pedohydrologic properties, such as volumetric moisture contents or matric suctions, in depths > 25 cm where ksat values are unknown.

DATA PREPARATION AND MODELLING

We predicted soil depth with a basic sine-cosine relation based on the slope angle, given by the equation:

$$z = -\frac{0.5}{COs(\beta)} * In(\sin(\beta))$$

where β is the slope angle in degree and 0.5 is a constant obtained from empirical observations[Pelletier & Rasmussen 2009].
A basic implication of the sophisticated and spatially-distributed hydrological model STARWARS [Van Beek, 2002] was used to predict both groundwater fluctuations and volumetric moisture content of the weathered load. Permeability of the lithic boundary was chosen according to the information of the lithological underground obtained from [Benvenuti, 2003].

Based on the regionalised ksat values, we used the approach of [Wösten et al., 1995] to estimate spatially distributed soil texture information. Consequently, the required soil

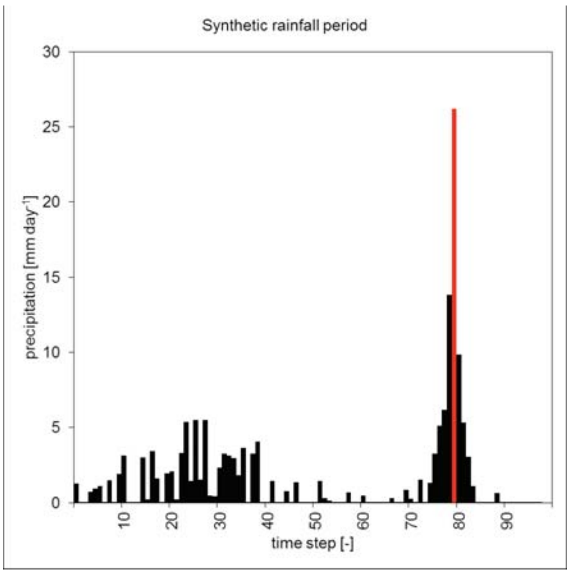

Fig. 4. Distribution of rainfall over the modelled period. The red bar shows an extreme event during the rainfall period at day 79.

parameters for the model were compiled with relations of pedotransfer functions, presented in Saxton & Rawls [2006] and Saxton et al. [1986]. In this regard, we calculated saturated moisture content, residual volumetric moisture content, air entry value, shape factor, dry bulk density and soil cohesion. The initial groundwater level as well as the volumetric moisture content of the soil column was set to 0.

Since continuous daily rainfall data were not available for our study area, synthetic precipitation values were created based on information about heavy rainstorms events that were recorded from meteorological stations from Borgo San Lorenzo and San Piero a Sieve (Fig. 4). The model was run for 100 time steps with each step representing one day.

RESULTS

In context of geographical hydrology, we define soil as the entire weathered material to the contact of a lithic boundary or the bed-

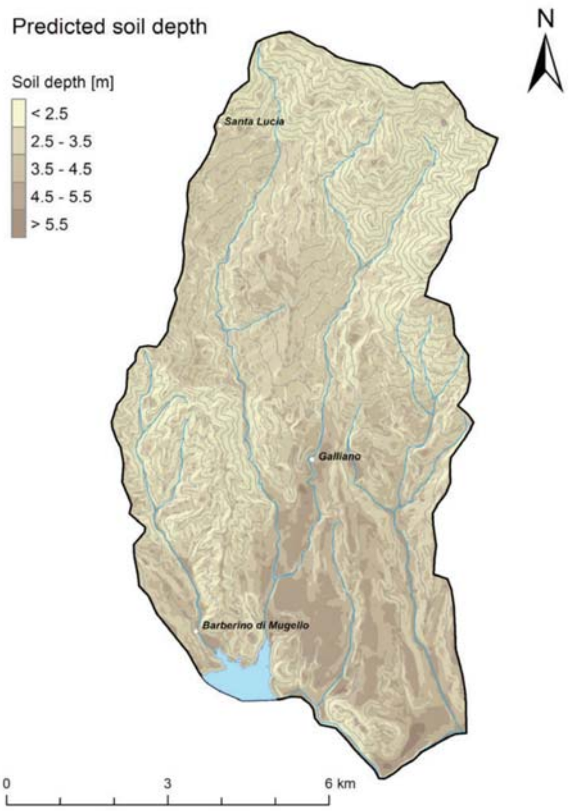

Fig. 5. Predicted soil depth for the Galliano catchment.

material, respectively. Most of the flat areas are located within the basin, where the corpus of the fluvio-lacustrine sediments is accumulated. Claystone, sandstone and partly marls with limestone lenses underlie the margins and hillslope environments. In this regard, it has to be considered that the weathered material is shallower and the distance to the lithic boundary is rather short. The results of our

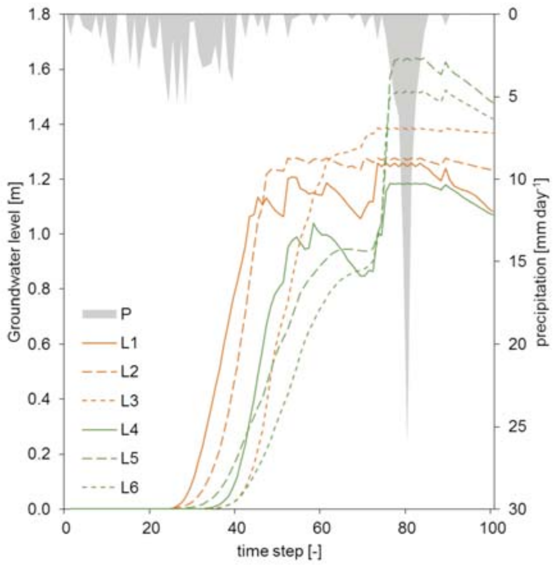

Fig. 6. Groundwater level response to rainfall (grey area; P) during the modelled period for six locations (L) within the catchment. Locations 1-3 (red lines) are located at the valley bottom. Locations 4-6 (green lines) are located on slopes (cf. Fig. 7).

soil depth approximation (Fig. 5) replicate the lithological conditions and the expected thickness of the soil mantle sufficiently for a proper hydrological modelling procedure.

Hydrological response and soil water fluctuations

The predicted groundwater level considerably increases between time steps 23 (L1 and L2) and 26 (L5 and L6) when daily rainfall frequently exceeds values of > 3.5 mm per day (Fig. 6). After a rapid increase to

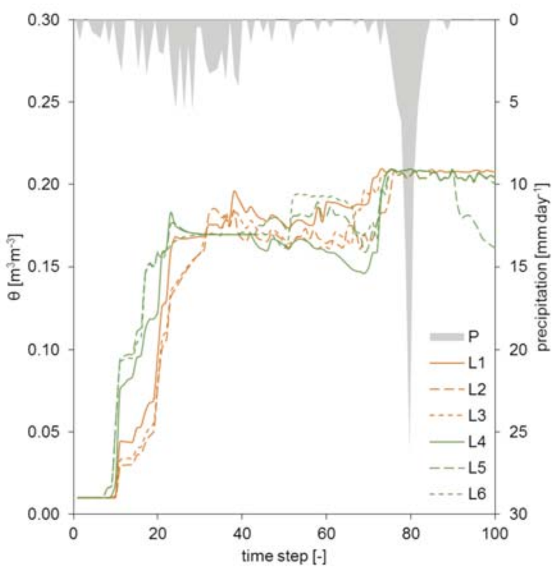

Fig. 7. Volumetric moisture content of soil columns at locations 1-6.

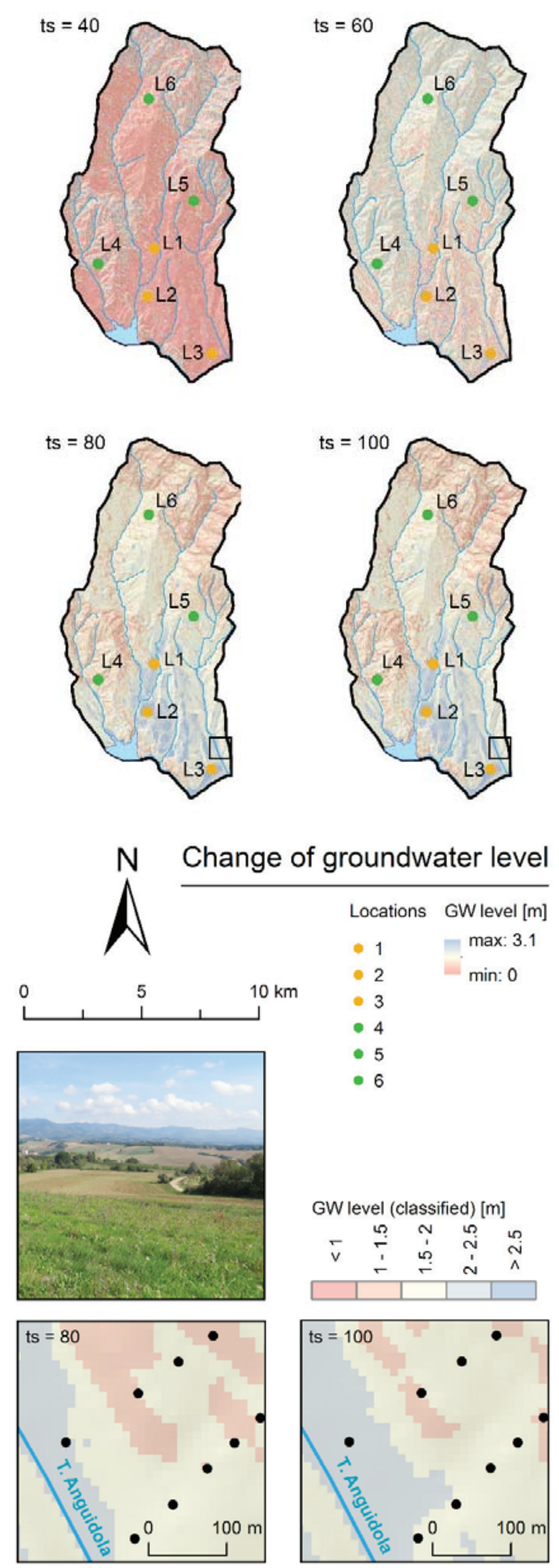

Fig. 8. Groundwater (GW) fluctuations for time steps 40, 60, 80 and 100.
The small figures show an investigated slope section (black dots: sample positions) and its groundwater level changes for time steps 80 and 100. We chose a classified colouring to show changes in the groundwater level for this location. The image illustrates the landscape setting of this slope section.

values between 0.9 m and 1.3 m locations 2, 3, 5 and 6 show equilibrium conditions, whereas groundwater level at positions L1 and L4drop to 1.1 or 0.8 at time step 69, respectively. All locations that are situated in rather flat areas at the valley bottom (L1-3) do not show response to incipient water input from the rainstorm at time step 69. In contrast, locations situated on hillslopes (L4-6) show all rather quick response, followed by a decline after time step 83.

Fig. 7 shows the changes in volumetric moisture contents (θ) for the locations L1-6. Moisture contents increase at all locations between time steps 8 and 11. L 4-6 show a rapid rise of moisture content after rainfall initiation up to 15 % or 18 % respectively between time steps 18 and 21. This rapid increase is followed by a stagnation and steady decrease until the end of the first rain period. L1-3 shows a delayed response of increase in moisture content to 17 % (L2) up to 19% (L1). The curves show swaying between time steps 30 to 70, followed by an increase up to 21 % coinciding with the rainstorm event.

DISCUSSION

The results shown in Fig. 6-8 indicate that locations on hillslopes do have quicker response to water input than those located in flat areas. This might be due to two reasons: First of all, soil thickness is presumably lower than in flat areas. Interflow within the soil column and runoff along the lithic contact can occur faster and more rapid. However, groundwater level rises rapidly when water reaches the lithic boundary and percolation through the soil column exceeds the infiltration capacity into the bed-material. In this regard, discharge along the lithic boundary has to be less than the amount of percolating water from above and the loss of infiltrated water into the bed-material. This considerably occurs, when the bedrock is rather impermeable, as it is the case for the slopes in our study area. Interestingly, the model results of the predicted water table in flat locations (L1-3) show equilibrium conditions with a decline after the heavy rainstorm between time steps 69-83 (Fig. 6). This might be explained by the fact that infiltrating water and water from the upstream areas balance the loss of water into the bed-material. In this regard, we presume that the rather coarse textures of the lacustrine sediments highly contribute to a desiccation of the overlaying soils.

The decent increase of volumetric soil moisture content of soils on slopes might be due to lower predicted soil depth at steeper locations and a faster recharge velocity than it could occur in deeper soils (Fig. 7). The steady decrease after reaching a local maximum of 15 % (L5) to 18 % (L 4) indicates that water has reached the lithic zone. Thus, percolation stops and water flow along the lithic contact can occur. However, this parameter depicts a very vague point of the model, since hydraulic conductivity of the bed material has been approximated. On the other hand, the lithological setting (e.g. calcareous claystone on slopes) could provide equilibrium conditions due to infiltration into the bed-material. L4-6 are located in hillslope environments, underlain by calcareous claystone as it was reported by Benvenuti [2003]. Consequently, infiltration into the bed-material is significantly reduced, which would promote the formation of an aquifer layer when deeper soil layers get close to saturation. However, it is more likely that the gentle decline of moisture content between time steps ~ 20 to ~ 70 at L4-6 is due to interflow loss of the soil column rather than to infiltration into the bed-material, since we set infiltration capacity of the lithic contact to zero at hillslope locations. Moreover, it is observable that the soil column does not reach saturated conditions between time steps 20 to 70. Saturation, however, is clearly apparent with beginning of the heavy rainfall period at time step 69. For all locations on slope positions, the soil reaches the maximum of saturated volumetric moisture content (~ 20 % - 21 %).

In contrast, locations 1 to 3 show a different response to the rainfall input. The delayed increase of moisture content compared to L4-6 is directly related to the deeper soils and thus, the higher potential of water retention. Fluctuations of soil moisture that can be observed between times steps 30 to 70 are most likely due to equilibrium conditions of infiltrating water from the surface into the soil and percolation from the soil into the bed-material. We considered the lithic boundary as not sealed and permeable to reproduce the hydropedologic conditions and granular structures of the lacustrine bed material. However, time steps 30 to 70 may be distinguished into two parts: a) the first part depicts the rainfall period from time steps 30 to ~ 38 where still infiltration conditions are existent; b) a dry period represented by time steps ~ 38 to ~ 68 where no rainfall input occurs.

Nevertheless, soil moisture fluctuations are comparable for both of the parts and do not change significantly. This relation indicates an input of interflow or runoff water from surrounding slopes and the catchment margins. This appears to be reliable because L1-3 are located on the less-inclined valley bottoms with higher specific catchment areas. Comparable to the locations on the slopes, L1-3 show an increase of volumetric moisture content with the beginning rainstorm event at time step 69 and reach their maximum of ~ 20 % - 21 %. In contrast to some of the locations on the slope (e.g. L5), infiltrated water does not exit the soil column and might reduce a drop of soil moisture, but stays constantly saturated. Interestingly, the findings report only a drop of soil moisture content at L5, which could be explained that the upslope area that contributes to water inflow into L5 is rather small. Thus, outflow might exceed inflow and thus a quicker reaction in soil moisture content.

The hydrological response of the soils tested in our model are in large part in line with observations of former studies[e.g. Garfagnoli et al., 2013]. The model results reveal a high absorption potential of the clayey soils during a long but moderate rainfall period (e.g. modelled time steps 0 to 40). This is due to the reduced infiltration capacity of the clayey soil and the respectively high thickness of the drainable soil mantle. Garfagnoli et al. [2013] also reported the relationships of thick clayey soils and their reduced infiltration and percolation capacity. Thus, the model output appear reliable considering dry soil conditions and a water absorption period of approx. 40 days until the soil column becomes nearly saturated. However, the results should be regarded as theoretical for several reasons:

1) even after dry season it remains doubtful whether the soil is fully parched. Thus, a residual volumetric moisture content would cause faster responses in water level changes and groundwater fluctuations.

2) Perched groundwater conditions due to structural diversity of soil texture within the soil mantle are not considered.

3) Hydrological parameters of the lithic contact zone or the lacustrine sediments that are underlying the soil were roughly estimated according to facies descriptions of Benvenuti [2003]. Water storage capacity and conditions of the aquifer layers are very difficult to establish and hence, our model input based on the above described hypothesis and derivation methods remain a first estimate.

A major critical point of the model output is the typical condition of Mediterranean clayey soils after a dry season. Cracks within the soil column can develop, when the soil moisture content drops dramatically during the dry season. Dilative, swellable or active clays such as Montmorillonite or Illite can cause these cracks under dry conditions. Garfagnoli et al. [2013) reported high ratios of clays in general (~ 51.02 %) and active clays in particular (~ 21.62 % Montmorillonite, ~ 27.65 % Illite). Hence, infiltration and percolation rates are massively increased. Under such conditions, it is expected that infiltrating water percolates much faster into deeper soil layers and cause much faster an increase of the groundwater level.

CONCLUSION AND OUTLOOK

In this study, we presented a first assessment of groundwater response and soil moisture fluctuations of a catchment of the Mugello basin in Tuscany during a synthetic rainfall period. Therefore, we applied a spatially-distributed and dynamic hydrological model. Hydropedologic parameters were obtained from in-field measurements of saturated hydraulic conductivity and soil texture. The results show that the rise of groundwater level is quite diverse comparing hillslope positions and sedimentation types. The same findings were observed for the changes in volumetric moisture content (θ) that is explained by the diverse lithological underground and the associated differences of soil properties. Moreover, the results show challenges and drawbacks of hydrological modelling in a landscape, where soils are partly separated from the underlying bed-material by a quite permeable lithic boundary and a respective high content of swelling clays is apparent. However, reliable and validated information about the landscape hydrology are fundamental for further analyses on sediment dynamics and related hydropedologic processes such as gravitative mass movements. Therefore, our results highlight the difficulties that are connected to hydrological modelling approaches in areas with a high variability in climatological and lithological conditions.

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